

# EXPLORING COUPLED SOLITONS IN MULTI-CORE OPTICAL FIBER

## FINAL REPORT

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AUGUST 10, 1995

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DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification .....	
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Availability Codes	
Dist	Avail and/or Special
A-1	

U.S. ARMY RESEARCH OFFICE

DAAH04-93-G-0079

RENSSELAER POLYTECHNIC INSTITUTE

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19951005 048

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## 1. Foreword

This project addresses a fundamental attack on a key current problem; how to optimize robust transmission of very large amounts of information in short times. Solitons offer a fundamental mechanism for high data rate and resistance to degradation of information. Coupled solitons offer a yet further enhancement of this capability by adding both parallelism and novel physical mechanisms. These novel physical mechanisms can enhance the resistance of an array of solitons to degradation of the soliton relationship. Maintenance of this relationship is typically essential to avoiding degradation of the information carried by the array.

As one might expect, the first attempts to experimentally investigate these phenomena identified both opportunities and barriers. Given the relatively little detailed knowledge about these structures, we have attempted to build up our capability for predicting their properties while at the same time identifying the nature of the experimental problems before investing substantial experimental resources.

We find valuable novel physical phenomena are expected. However, practical realization of these phenomena will probably require fabrication techniques that can maintain the refractive indices of the two cores to better than one part in  $10^6$  over tens of meters or more. The basic problem is maintaining a well defined phase relationship of the optical carrier fields on adjacent cores over tens of meters despite the tendency of the materials and structures to introduce small differences in the phase relation.

This work is unusual in the large amount of work performed for the small amount of resources expended. We are particularly indebted to several associates for very substantial contributions at no cost. A move from Rensselaer Polytechnic Institute in Troy, N.Y. to the University of Alabama in Huntsville, Alabama required termination of the work after one year, despite promising calculational predictions, substantial experimental progress, and clear identification of the specific barrier to further progress. We recommend further work and note the numerical simulations are very encouraging as regards the potential advantages of this concept. The most likely barrier to accessing these advantages appears to have been clearly identified.

We recognize the very strong performance in the numerical simulation area on this topic by Dr. Joseph W. Haus and by students supervised by him at Rensselaer, at minimal cost to this contract. The principal investigator also wishes to recognize the preparation, characterization, and donation at no cost, of dual core fiber by Graham Atkins and others of the Optical Fiber Centre at the University of Sydney in Sydney, Australia. Without this fiber and the related work, this project would not have been possible.

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#### 4. A. Statement of the Problem Studied

The task has been to explore coupled soliton arrays in multiple-core optical fiber. The physics of interest is that solitons propagating on adjacent (within a few core diameters), but physically distinct, lowest order mode cores exhibit nonlinear interactions that can be characterized as quasi-forces. These quasi-forces arise from perturbations of the soliton envelope that result in changes in soliton spectra and hence velocity via the modified self phase modulation. These quasi-forces can be attractive or repulsive, and can be realized in combination. The implication is that forces may be identified that could help maintain the relationship of solitons in an array despite unintended perturbations that would otherwise degrade the relationship of the solitons.

We have used experiments and numerical simulations to explore the nature of these quasi-forces between solitons on adjacent cores of multi-core fiber and to identify pathways to realizing structures and mechanisms of practical interest. We anticipate we will identify opportunities, as, e.g., for carrying rigorously synchronized clock, address, and switching information along with data despite otherwise potentially disruptive mechanisms.

The prior theoretical work most relevant is that of Abdullaev et al ("Dynamics of solitons in coupled optical fibers," F. Kh. Abdullaev, R.M. Abrarov, and S.A. Darmanyan, *Optics Letters* **14**, 1989 (131-3). These authors showed one can expect quasi-forces between solitons on adjacent cores that can be either repulsive or attractive depending on the relative phase of the optical carrier fields constituting the solitons. This base grant has sought an experimental confirmation of that prediction. We also have a separate AASERT grant to pursue numerical simulations of these coupled soliton states.

The theoretical problem has been one of describing the soliton interaction more precisely and completely than had been described by Abdullaev. Abdullaev et al used approximations that limited the accuracy of their predictions and they only explored a very limited class of examples. The group also did not address the case of a single soliton on one core of a dual core fiber or the properties of periodic trains of interacting pulses.

The experimental problem has been to obtain dual core fiber with properties such as core spacing and length, pulse trains, and diagnostic equipment that enable an experimental investigation of the phenomena of interest. The generation of the needed pulses, pulse trains, and diagnostic equipment has been the subject of a large fraction of our experimental effort. We are indebted to AFOSR for the support of most of this aspect of the work.

The particular experimental and theoretical goals of this proposal have been to use the numerical simulations and theory to predict the behavior of the coupled solitons and the experimental capability to verify or disprove the predictions. The goal was to measure and observe in some detail the properties of coupled soliton states in dual core fiber. A first step was identification of the conditions under which measurable coupling of soliton pairs might be observed and then realization of those conditions and documentation of the observed behavior and comparison with theory.

#### 4. B. Summary of the Most Important Results

Because of the PI's relocation from one institution to another it was necessary to terminate this grant before the work could be completed in the intended manner. We have however obtained a substantial body of valuable information on this problem for very modest expenditure of resources. We are indebted to collateral support from AFOSR, OFTC, MICOM, and Dr. Haus for much of the progress. We give some of the results of the numerical simulations here and the experimental results. Other results from the numerical simulation work are given in the AASERT final report.

The essential findings are:

- (1) Numerical simulations predict that coupled soliton states can be realized.** Simulations by Dr. Haus and his students identified a regime where we would expect to experimentally observe the coupled soliton phenomena. Core spacings of about 40 microns, solitons of about 300 fs duration, and fiber lengths of order of 20 meter appear appropriate. In general for the picture of solitons interacting via these quasi-forces to be useful, linear coupling length for the dual core fiber must be greater than the soliton period or dispersion length. This condition arises in that the soliton properties have a significant influence on the pulse properties over distances less than a coupling length if the soliton properties are to significantly influence the nature of the coupling. This is a common sense conclusion; however, it is encouraging as regards the accuracy of the theory that it rather rigorously supports this conclusion.
- (2) The interaction of coupled soliton pairs on adjacent cores is highly sensitive to the relative phase of the optical carrier fields constituting the solitons on the adjacent cores.** The theory and simulations show that the interaction of coupled soliton pairs is highly sensitive to the relative phase of the optical carrier fields that constitute the interacting solitons. The sign of the interaction depends on the relative phase and the interaction can thus change from attractive to repulsive depending on the relative phase. This is a relatively intuitive conclusion. The physical basis of the soliton-soliton interaction is the modification of the soliton envelope that results from the addition of the evanescent field of the neighboring pulses. If the relative sign of the field changes, it is quite plausible that the nature of the interaction drastically changes.
- (3) The relative phase of the carrier fields can easily change due to small differences in the optical paths of the light on the two fiber cores.** Even though the two fiber cores are in close proximity and the material is very similar, there tend to exist small differences in the refractive index that lead to significant differences in the relative optical phase of the optical carrier fields on adjacent cores. For a difference in refractive index of one part in  $10^6$ , e.g., the optical phase delay is a significant fraction of  $\pi$  radians in a distance of 10 cm.
- (4) Bending of dual core fiber can alter the coupling ratio.** Bending of dual core fiber in the plane including the pair of cores can significantly alter the coupling between the cores. This can be minimized by holding the fiber straight under tension or using very large radius bends with the plane of the pair of cores lying normal to the radius of the bend; however, this may not be practical in many applications.

**(5) Experiments produced modelocked laser oscillation in a laser including dual core fiber.** We have succeeded in actively modelocking a fiber laser that includes a 20 meter long section of dual core fiber having a 40 micron core separation (obtained from the Optical Fiber Technology Center (OFTC) at the University of Sydney in Sydney, Australia). See Fig.1 for a diagram of the laser. We did not observe shorter pulses or more stable operation as compared with the same laser with a section of single core lowest order mode fiber of the same length.

**(6) We observe little difference in the laser performance on introducing the 20 meter section of dual core fiber.** There is little difference between the modelocked laser including dual core fiber and a laser using only conventional single core fiber. There did seem to be a lower threshold for the dual core fiber laser than we anticipated. Introducing the 20 meter long section of dual core fiber and two free space regions needed to introduce the section of dual core fiber did not decrease the average power out from the laser. This was surprising, since each free space section was supposed to have introduced at least 50% loss. We do not have a simple explanation for this observation at this time. More research needs to be done to explore this phenomenon.

**(7) We do observe a reduction in pulse duration on introducing a 20 meter section of conventional single mode fiber and means for polarization switching in place of the dual core fiber.** We tested the capacity of our modelocked laser as regards reducing pulse duration by nonlinear shaping by replacing the 20 meter long section of dual core fiber with a 20 meter long section of single core fiber and components for providing polarization shaping of the short pulse as it propagated on that section of the laser. We observed a reduction of the pulse duration from order of 10 psec to as short as 720 fsec.

**(8) We conclude that the dual core fiber is less effective than the polarization rotation in reducing the duration of short optical pulses.** The dual core fiber does not hinder active modelocking, but also is not as effective in producing short pulses. This is consistent with the theoretical predictions. The theory indicates that while the dual core fiber will sustain a soliton of short duration propagating on a single core the modelocked laser will not reduce the duration of a longer pulse.

**(9) The variation in refractive indices between cores severely hinders experimental realization of coupled soliton states over distances large compared to 10 cm and is the most likely reason for the similarity in behavior of the single and dual core fibers.** Detailed studies by the Optical Fiber Technology Center (OFTC) at the University of Sydney in Sydney, Australia, indicate that small refractive index variations between cores (less than one part in a million) cause a dephasing which decouples soliton states in the two cores.

**(10) We conclude that the difficulties in maintaining the phase relationship of optical fields in adjacent cores over distances greater than 10 cm is the most probable limiting barrier.** At this time the most likely difficulty hindering observation of the predicted coupled soliton states is the uncontrolled variation in refractive indices in the two cores. The OFTC group that fabricates the fiber has done careful tests and finds this variation is a uniform problem in all of the dual core fiber tested. Our numerical simulations show that these variations are sufficient to prevent occurrence of the predicted behavior. Given this difficulty it appears desirable to address this problem in the next efforts on this technology.

**(11) The practical problem of reducing the variations in refractive indices so as to realize the benefits of coupled soliton states is difficult, but possible solutions may exist.**

Fabrication techniques at this time are not adequate to reduce the variations between refractive indices in the two cores to the level required to achieve coupled soliton states. Correction techniques have, however, been identified. For example, workers at OFTC have irradiated a specially doped dual core fiber with uv light so as to change the refractive index of one core while monitoring the real time transmission of the fiber. They found they could tune the index difference to a point where the desired coupling processes were observed. We are also using numerical simulation as a means of exploring alternative solutions to this problem. While a solution may be difficult, we believe that it is likely a solution can be found. That search would be a good topic for subsequent work.

**(12) In general we conclude that dual and multiple core fiber structures should be pursued with an emphasis given to solving the dephasing caused by variations in the refractive indices between cores.** The opportunities offered by this new technology, the demonstration of successful fabrication of dual core fiber and its use in modelocked laser oscillators, the apparent restriction of applications by the one primary difficulty of a variation in refractive indices between cores, and the existence of potential solutions recommend attention to solution of the latter problem.

### **Details of Experimental Work**

**Dual core fiber:** We acquired three samples of dual core fiber from the Optical Fiber Technology Center at the University of Sydney in Sydney, Australia. The core separations were 14.47  $\mu\text{m}$ , 19.22  $\mu\text{m}$ , and 41.9  $\mu\text{m}$ . The lengths were each 20 meters. All three fibers were elliptical with the ovality being greater for fibers with a greater core separation. The fibers had a relatively high absorption loss at 1550 nm of 50 to 100 dB/km due to water overtone absorption.

**Fusion Splicing:** It was difficult to fusion splice single core to dual core fiber. We accomplished a few such splices, however, it was relatively easy to couple from free space to either core and the free space coupling was the primary coupling method used. Future work might address some of the difficulties in fusion splicing dual and multiple core fiber.

**Bending:** The dual core fiber was sensitive to bending. To make it usable the dual core fiber was wound on a very large radius (approximately half a meter) specially fabricated for this application. In general, bends should be minimized and then confined to bends normal to the plane of the two cores. A study of the role of bending and means for avoiding undesirable bend induced coupling appears appropriate.

**Laser configuration:** We constructed a laser as shown in Fig. 1 that included the dual core fiber. The concept tested here is that of enhanced pulse shortening produced by the predicted preferential loss of energy by the lower energy components of the short pulse. (The numerical simulations predicted that solitons could be realized having durations of order of 300 fsec in fiber having 40 micron core spacing. See final AASERT report.)

**Laser Parameters:** The overall length of the laser was 53 and 1/3 meters including the 20 meter section of dual core fiber. The dual core interfaced with the remainder of the laser through two free space regions where high quality lenses and mechanical positioners were used at the interface. The laser output power was 42 mW corresponding to an internal power of 60 mW. One observation that remains unexplained was that introduction of the

# Dual Core Laser Setup

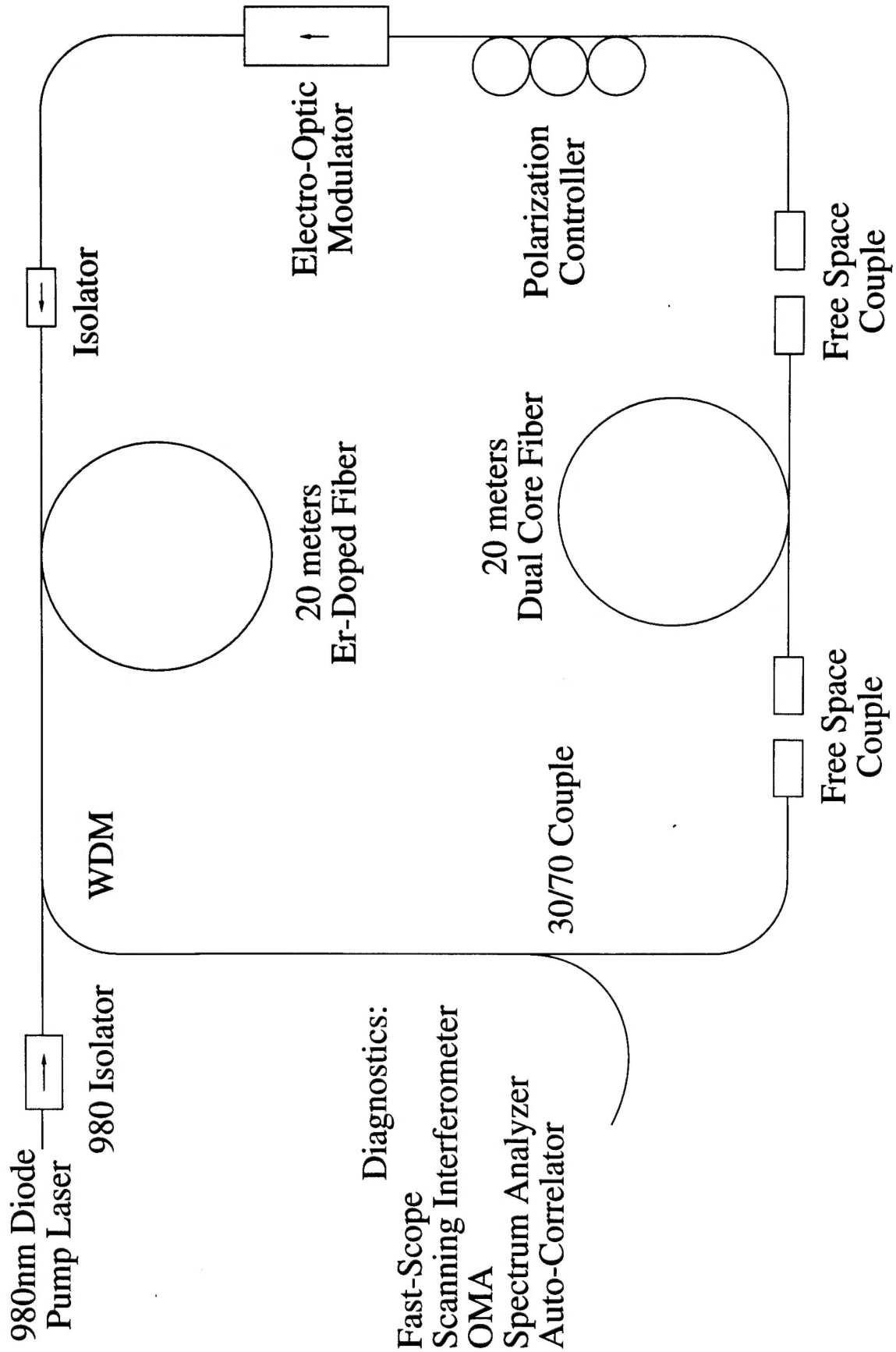


Figure 1

dual core fiber including the two free space regions in place of the continuous single core fiber resulted in no decrease in output power. Normally we would expect at least 6 dB additional loss from the two free space regions and an intrinsically higher absorptive loss in the dual core fiber as compared to the single core fiber ring.

**Repetition Rate:** We explored a range of repetition rates from 800 Hz to 1.8 GHz. We did not find a marked dependence on repetition rate. The majority of our data was taken at 1.35 GHz.

**Pulse durations using active modelocking:** An autocorrelator was built and used to measure the modelocked pulses generated by the laser that included the dual core fiber section. The pulses produced by active modelocking using a AT&T LiNbO<sub>3</sub> Mach-Zehnder modulator measured approximately 5.5 picoseconds duration. Since the numerical simulations predicted the dual core effects might not be evident unless the pulse durations were order of 1 picosecond or less we explored hybrid modelocking as a means of further testing the dual core fiber action.

**Pulse durations using hybrid modelocking:** In order to shorten the pulses to the order of 1 picosecond, we built a laser using single core-single mode fiber that included a polarization switching capability using retarder plates as shown in Fig. 2. This configuration adds polarization shaping, producing pulses of 700 femtosecond duration. This new laser now produced pulses short enough for use with the dual core fiber, however, at this point we were informed of the fabrication problems with the dual core fiber and therefore it was never added to this laser.

**Refractive index variations:** The work on the influence of refractive index variations was done by G.R. Atkins, J.W. Arkwright, and S.J. Hewlett of OFTC. We have private communications from them as well as the referenced findings. Further information regarding the private communications can be accessed by contacting the PI.

**Experimental conclusions:** We have been able to construct modelocked lasers that include sections of dual core fiber and operate them as well as or better than single core fiber lasers where careful direct comparisons have been made. Such careful comparisons were made for actively modelocked configurations. We have not made such careful comparison for passive modelocking as this project ended before that work could be done.

#### **Other information that may assist the ARO Program manager in evaluation of progress and accomplishments**

Special efforts are being made to include and train US citizens: U.S. citizen graduate students, Matt Nielsen, Walter Kaechele, and Ken Hamilton, participated in the group activities during this time period. U.S. citizen undergraduates, Senter Reinhardt, Rachel Flynn, and Nicholas Vitalis, also participated in the group activities during this time period. The research and the work with students is being addressed with a goal of preparing and interesting more US students in the high performance optical information handling work.

Special efforts are being made to strengthen national laboratory and university relations: Visits were made to MICOM at Redstone Arsenal, USASSDC, ARO at Triangle Park, MSFC NASA, Rome Laboratory, and Eglin AFB. MICOM personnel visited UAH, Rome Laboratory personnel visited RPI.

# Polarization Switch Laser Setup

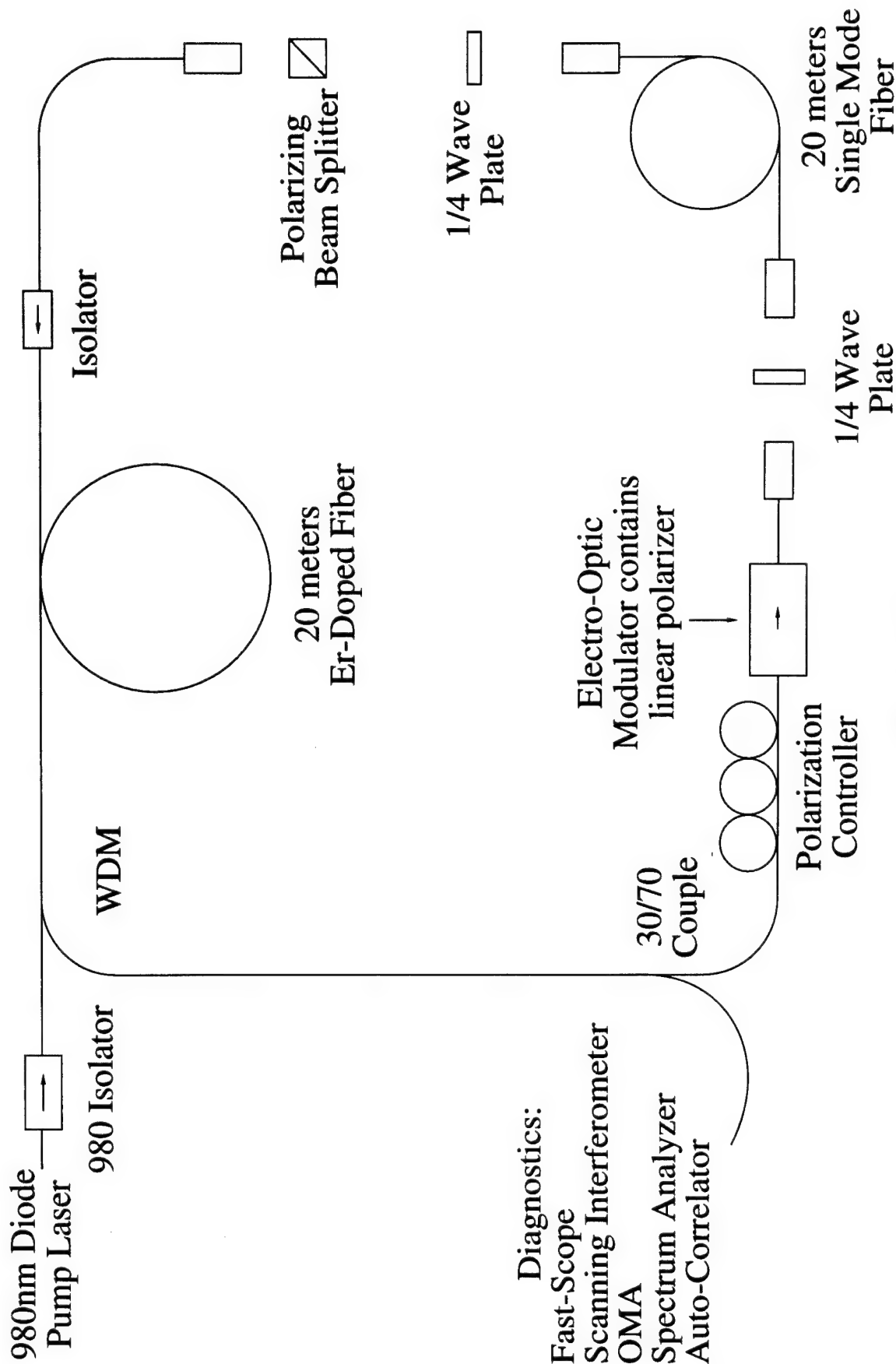


Figure 2

### **Termination of the grant**

Please note that we found it necessary to terminate this research grant because the PI moved from Rensselaer Polytechnic Institute to University of Alabama in Huntsville. This termination should not be regarded as a conclusion that the work should be abandoned, but rather a necessary consequence of moving our research facilities. We have delayed submission of a proposal for follow on work because of an absence of current funds and hope to resume work on this important topic in the near future.

### **Further Work**

We believe the very positive predictions of the numerical simulation work, the success of the OFTC in Sydney and workers at Southampton in fabricating dual core fiber , and our ability to include dual core fiber successfully in ultrashort pulse lasers recommends further work.

A logical focus of further work is on means of handling the dephasing influence of variations in the refractive index difference between the adjacent cores of dual core and multicore fiber. Means have been identified for handling this difficulty and we are exploring strategies for yet further means of correction.

#### **4. C. List of publications and technical reports published**

1. "Soliton Interactions on Dual Core Fibers", S.L. Doty, J.W. Haus, Y.J. Oh and R.L. Fork, submitted to Physical Review E, in fall 1994. (has been published as of this writing)
2. "Polarization Distortion in Birefringent Fiber Amplifiers", J. W. Haus, J. Theimer and R.L. Fork. Submitted to Photonics Technology Letters September 1994. ((Has been published as of this writing).
3. "Robust Operation of a Dual-core Fiber Ring laser", Y.J. Oh, S.L. Doty, J.W. Haus and R.L. Fork. JOSA B, in press, 1995.
4. "Soliton Repulsion Logic Gate," with Y. J. Oh and R. L. Fork Opt. Lett., submitted (1995).

#### **PhD Theses**

"An Investigation of Soliton Interactions on Dual Core Fibers" by Sandra Doty, RPI June 1994

"Models of Mode-locked Fiber Lasers and Soliton Logic Gates", YunJe Oh, Defense Date: August 1995.

(Note: Prof. Joseph Haus provided the principal supervision for these numerical simulation theses)

#### **Papers presented orally**

**Non-conference oral presentations:** CREOL(2), Naval Research Laboratory, UAH(3), Alabama A&M, Worcester Polytechnic, Boston University, MICOM, SSDC.

#### **Conference oral presentations:**

"Robust Operation of a Dual-core Fiber Ring laser", Y.J. Oh, S.L. Doty, J.W. Haus and R.L. Fork, QTuG7, Quantum Electronics and Laser Science Meeting in Baltimore 1995.

"Dual-core fibers: coupled solitons and amplifiers", S.L. Doty, Y.J. Oh, J.W. Haus, R.L. Fork. ML4, OSA Annual Meeting in Dallas (1994)

"Dynamics of Soliton Arrays in Architected Guided Structures". S.L. Doty, R.L. Fork and J.W. Haus, OSA Annual Meeting, Toronto (1993)

#### **4. D. List of all participating scientific personnel**

R. L. Fork, Professor, RPI, supervised experimental work dealing with the the fiber laser pulse generation and interacting solitons in dual core fiber relevant to the project. Supervised five graduate students and four undergraduate students.

Joseph Haus, Professor, RPI, supervised extensive numerical simulation work dealing with the fiber laser pulse generation and interacting solitons in dual core fiber relevant to the project. Supervised two PhD students who worked primarily on dual core fiber problems. Note that Dr. Haus received no direct Army support himself.

Michael Scalora: Research Associate, UAH. Dr. Scalora was recently a member of the Quantum Optics group at MICOM. Dr. Scalora ran extensive numerical simulations of solitons on dual core fiber and contributed strongly in discussions and development of our understanding of the nonlinear physics of ultrashort optical pulses on dual core fiber.

Jeff Strait, Professor, Williams College, spent sabbatical at RPI. Participated strongly with group in planning and executing experiments and supervising students at RPI during 1993.

Graham Atkins, Optical Fiber Technology Center, University of Sydney, Sydney Australia, fabricated and evaluated dual core fiber used in experiments. An important source of high quality dual core fiber.

#### **Participating students, degree status and form of support**

Sandra Doty - PhD completed 1994- primary support DOE, used equipment provided by ARO

Kalwant Singh-PhD completed 1994-primary support AFOSR, used equipment provided by ARO

James Theimer- PhD anticipated 1995 - primary support from Rome Laboratory, used equipment provided by ARO

Yun Je Oh, PhD anticipated 1995, primary support from RPI, limited support from AFOSR

Matt Nielsen- PhD anticipated completion 97- primary support from DOE, limited support from AFOSR, used equipment provided by ARO.

Walter Kaechele- PhD anticipated completion 97-primary support from DOE, summer support from Rome Laboratory, used equipment provided by ARO

Undergraduate students:

Senter Reinhardt, support from AFOSR AASERT, used equipment provided by ARO

Rachel Flynn, support from AFOSR AASERT, used equipment provided by ARO

Nicholas Vitalis, used equipment provided by ARO

Ken Hamilton, used equipment provided by ARO

## **5. Report of Inventions by Title**

"Modelocked dual core laser utilizing polarization shaping."

We identified a structure that could, in principle, exhibit the operation predicted by the numerical simulation. This laser will not be practical without a solution to the problem of refractive index variation. We regard this structure as an invention of potential interest should the problem of the difference in refractive indices be solved.

## **6. Bibliography**

"Dynamics of solitons in coupled optical fibers," F. Kh. Abdullaev, R.M. Abrarov, and S.A. Darmanyany, Optics Letters **14**, 1989 (131-3).

# REPORT DOCUMENTATION PAGE

Form Approved  
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE

8/10/95

3. REPORT TYPE AND DATES COVERED

Final

4. TITLE AND SUBTITLE

Exploring Coupled Solitons in Multi-Core Optical Fiber

5. FUNDING NUMBERS

DAAH04-93-G-0079

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Rensselaer Polytechnic Institute  
110 8th ST.  
Troy, NY 12180

8. PERFORMING ORGANIZATION  
REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Research Office  
P. O. Box 12211  
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING  
AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

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12a. DISTRIBUTION / AVAILABILITY STATEMENT

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12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

We use calculations and experiments to explore dual-core optical fiber regarding its potential for robust transmission of coupled solitons at high data rate. The encouraging findings are that physical mechanisms can be identified that appear valuable to improved information transmission. Typical core separations, e.g., 14 to 40 microns, permit coupling and interaction of solitons, and also provide spatially distinct optical paths. Numerical simulations predict attractive, repulsive, and neutral combinations of effective forces between solitons on adjacent cores. The experiments show that substantial lengths, e.g., 20 meters, of dual core fiber will support not only, transmission of pulses approximating lowest order solitons, but modelocked laser oscillator operation as well. A remaining, and perhaps the single primary barrier, to practical realization of these states is the small (order of one part in  $10^6$ ), as yet unavoidable, difference in refractive index between adjacent cores in realizable multicore fiber. Potential solutions to the problems caused by small refractive index differences can be identified and further work is recommended.

DTIC QUALITY INSPECTED 5

14. SUBJECT TERMS

dual core fiber, coupled solitons, harmonically modelocked  
fiber lasers

15. NUMBER OF PAGES

16

16. PRICE CODE

17. SECURITY CLASSIFICATION  
OF REPORT  
UNCLASSIFIED

18. SECURITY CLASSIFICATION  
OF THIS PAGE  
UNCLASSIFIED

19. SECURITY CLASSIFICATION  
OF ABSTRACT  
UNCLASSIFIED

20. LIMITATION OF ABSTRACT  
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